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Engineering and Design
RELIABILITY ANALYSIS OF NAVIGATION LOCK AND DAM MECHANICAL AND ELECTRICAL EQUIPMENT

1. Purpose

This engineer technical letter (ETL) provides guidance for assessing the reliability of mechanical and electrical systems of navigation locks and dams and for establishing an engineering basis for major rehabilitation investment decisions. This cover letter defines terms and concepts associated with reliability analysis. Appendix B lists Web sites that contain information useful to reliability studies, Appendix C describes the acquisition of failure data, Appendix D gives an example reliability analysis for mechanical equipment, Appendix E gives an example reliability analysis for electrical equipment, Appendix F gives an example of lock and dam mission reliability, and Appendix G evaluates a non-series-parallel system.

2. Applicability

This ETL is applicable to all USACE Commands having Civil Works responsibilities. It applies to all studies for navigation lock and dam projects.

3. References

Publications are listed in Appendix A.

4. Distribution Statement

Approved for public release, distribution is unlimited.

5. Background

a. Navigation lock and dam facilities are an important link in the Nation's transportation system. Their mission is to maintain the navigable waterways and allow both cargo transport and recreational traffic between adjacent segments of the waterways. The mechanical and electrical components at these facilities function as systems to operate the various gates and valves. Breakdowns and poor performance of these systems can cause delays to navigation and adversely affect the overall national economy.

b. Lock and dam major rehabilitation projects began being budgeted under the Construction, General, and Flood Control, Mississippi River and Tributaries appropriation account in Fiscal Year

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This ETL supersedes ETL 1110-2-549 dated 30 November 1997.

(FY) 1993. To qualify as major rehabilitation projects, the work activities must extend over two full construction seasons and the total required implementation costs must be greater than a certain minimum threshold. The threshold amounts are adjusted annually for inflation as published in the Army Programs – Corps of Engineers Civil Works Direct Program – Program Development Guidance. To compete successfully as new starts, major rehabilitation proposals must be supported by the same level of economic analysis as new water resource projects. Chapter 3 of Engineer Regulation (ER) 1130-2-500 establishes policy for major rehabilitation at completed Corps projects. Chapter 3 of Engineer Pamphlet (EP) 1130-2-500 establishes guidance for the preparation and submission of Major Rehabilitation Project Evaluation reports for annual program and budget submissions.

c. The rehabilitation of mechanical and electrical equipment is usually included as part of the overall project. Rehabilitation may include replacement and/or reconditioning to restore or improve a system to a like-new condition. The rehabilitation may be considered from various perspectives. It may be necessary to restore existing equipment that has deteriorated with time or failed in service; or equipment may become obsolete, and replacement might be desired to upgrade the equipment to modern standards. The Major Rehabilitation Evaluation reports and supporting information will have to provide evidence of criticality with a certain level of detail based on specific uniform engineering criteria. Reliability assessments based on probabilistic methods provide more consistent results and reflect both the condition of existing equipment and the basis for design.

d. Further guidance for the reliability evaluation of hydropower equipment has been published in ETL 1110-2-550 and Mlakar 1994.

6. Reliability Concepts and Definition of Terms

a. *Definition of terms.*

(1) *Component.* A piece of equipment or portion of a system viewed as an independent entity for evaluation, i.e., its reliability does not influence the reliability of another component.

(2) *System.* An orderly arrangement of components that interact among themselves and with external components, other systems, and human operators to perform some intended function.

(3) *Failure.* Any trouble with a component that causes unsatisfactory performance of the system.

(4) *Hazard function or failure rate.* The instantaneous conditional probability of failure of an item in the next unit of time given that it has survived up to that time. It is the mean number of failures of a component per unit exposure time.

(5) *Reliability.* The probability that an item will perform its intended function under stated conditions, for either a specified interval or over its useful life.

(6) *Basic reliability.* Measure of the demand for maintenance and logistic support of a system caused by unreliability.

(7) *Mission reliability.* Measure of operational effectiveness of a system. A mission reliability prediction estimates the probability that items will perform their required functions during a mission.

(8) *Unsatisfactory performance.* Substandard operation; partial or complete shutdown of the system; operation of safety devices; unexpected deenergization of any process or equipment.

b. *Measures of component reliability.*

(1) *Reliability function.* The continuous probabilistic approach to item reliability is represented by the reliability function. It is simply the probability that an item has survived to time *t*. The mathematical expression can be summarized by

$$R(t) = P(T \geq t) \tag{1}$$

where

$R(t)$ = reliability of the item, i.e., probability of success

$P(T \geq t)$ = probability that the time to failure of an item will be greater than or equal to its service time

T = time to item failure

t = the designated period of time for the operation of the item

Conversely, the probability of failure $F(t)$ is simply

$$F(t) = 1 - R(t) \tag{2}$$

(2) *Hazard function or failure rate.*

(a) The failure rate or hazard function $h(t)$ represents the proneness to failure of a component as a function of its age or time in operation. It reflects how the reliability of a component changes with time as a result of various factors such as the environment, maintenance, loading, and operating condition. From Modarres (1993) it can be shown that

$$f(t) = \frac{-dR(t)}{dt} \tag{3}$$

$$h(t) = \frac{f(t)}{R(t)} \tag{4}$$

where $f(t)$ is the probability density function (pdf). This is a mathematical description for the curve approximation of the number of the probable occurrences of a specific random variable (i.e., the failure of a component for use in this ETL).

(b) The hazard function or instantaneous failure rate is the instantaneous conditional probability of failure of an item in the next unit of time given that it has survived up to that time. The hazard function can increase, decrease, or remain constant. It has been shown that the failure rate behavior of most mechanical and electrical engineering devices follows that shown in Figure 1. This is known as the *bathtub curve*. Region A represents a high initial failure rate, which decreases with time to nearly constant. This is known as the infant mortality region and is a result of poor workmanship or quality control. Region B represents the useful life phase. Here, failures occur because of random events. Region C represents the wear-out phase where failures occur due to complex aging or deterioration.

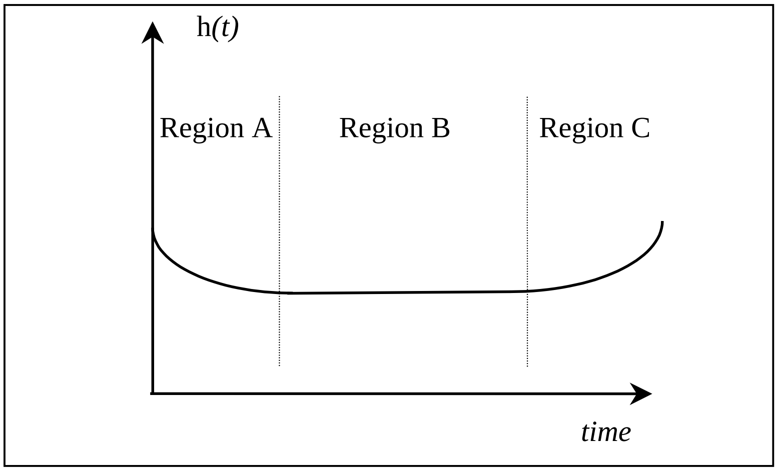

Figure 1. Typical bathtub curve

(c) The flat random or chance failure region (Region B) of the curve for electromechanical devices is much longer than the other two regions. Electrical devices exhibit a much longer chance failure period than mechanical devices. Methods presented in this ETL will attempt to determine reliability and predict the characteristics of Regions B and C of the bathtub curve for mature equipment using the common continuous distribution functions discussed in the next paragraphs. The infant mortality region (Region A) will not be directly discussed in this ETL since the equipment considered for major rehabilitation projects usually falls into Regions B or C.

(3) *Exponential distribution.*

(a) The exponential distribution is the most commonly used distribution used in reliability analysis. The reliability function is

$$R(t) = e^{-\lambda t} \tag{5}$$

where

t = time

λ = failure rate

This distribution can be used to represent the constant hazard rate region (Region B) of the bathtub curve. The hazard function for the exponential distribution remains constant over time and is represented as simply λ:

$$h(t) = \lambda \tag{6}$$

Plots of the reliability and hazard functions for the exponential distribution are shown in Figures 2 and 3, respectively.

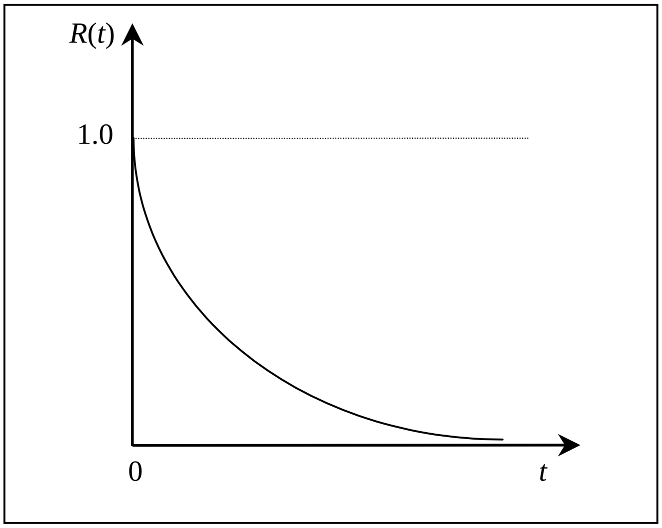

Figure 2. Reliability function for exponential distribution

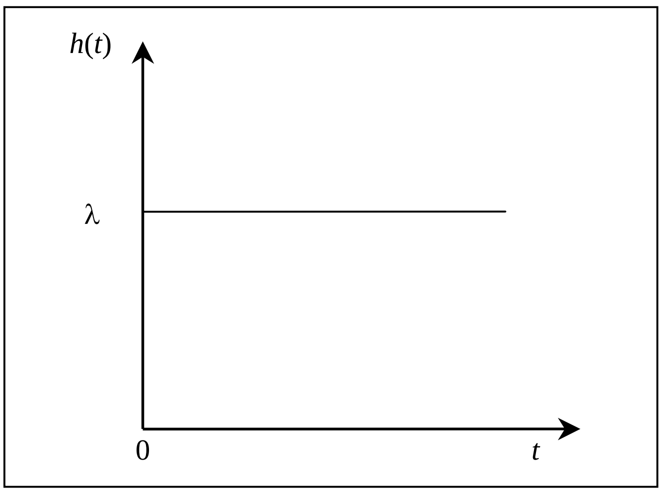

Figure 3. Hazard function for exponential distribution

(b) The average or mean of the exponential life distribution is the Mean Time to Failure (MTTF). It is the average length of life of all units in the population. It has significance in that the reciprocal of the hazard rate is equal to the MTTF:

$$\text{MTTF} = \frac{1}{\lambda} \tag{7}$$

(4) *Weibull distribution.* The Weibull distribution is a generalization of the exponential distribution. This distribution covers a variety of shapes, and its flexibility is useful for representing all three regions of the bathtub curve. The Weibull distribution is appropriate for a system or complex component made up of several parts. The Weibull reliability function is

$$R(t) = \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \tag{8}$$

where

α = the scale parameter or characteristic life

β = the shape parameter

For $0 < \beta < 1$, the Weibull distribution characterizes wear-in or early failures. For $\beta = 1$, the Weibull distribution reduces to the exponential distribution. For $1 < \beta < \infty$, the Weibull distribution characterizes the wear-out characteristics of a component (increasing hazard rate). The Weibull hazard function is

$$h(t) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1} \tag{9}$$

Plots of the reliability and hazard functions for the Weibull distribution are shown in Figures 4 and 5, respectively.

c. *General data required*. Reliability analysis provides the best estimate of the reliability anticipated from a given design within the data limitations and to the extent of item definitions. The required data are dependent on the availability and depth of analysis required. Mechanical and electrical components are typically complex and made up of many different parts, each with several modes of failure. These failure modes are associated with many ambiguous variables such as operating environment, lubrication, corrosion, and wear. Historic data for lock and dam equipment have not usually been available. Lock and dam equipment for which data are not available requires the analysis to be completed using data from larger systematic samples of similar equipment such as the published failure rate data in Reliability Analysis Center (1995). Failure rate data can also be obtained by multivariate methods developed in Naval Surface Warfare Center (1992). Prior to any reliability determination, investigations should be conducted to gain a thorough knowledge of the mechanical and electrical requirements and layouts, to identify equipment deficiencies, and learn the project history and future demands.

d. *Internet Web site*. An Internet Web site (Appendix B) has been established as a means to collect both historical and recent failure data for lock and dam mechanical and electrical equipment. It is intended that the data will be continually collected and compiled so that accurate failure rate tables can be developed. The data will better represent lock and dam equipment. The most important benefit is that the most current failure data for Corps mechanical and electrical equipment will be available to engineers doing the reliability work for future projects. In addition, it will provide a central reference source for operations and engineering personnel to check when failures occur to see if there are common problems with installed equipment. The most current data has been included in Appendix C. Engineering and operations personnel are encouraged to input available failure data. The Web site should be checked for the latest failure rate data when a reliability analysis is being developed.

7. Engineering Reliability Analysis

Assessment of the reliability of a system from its basic elements is one of the most important aspects of reliability analysis. As defined, a system consists of a collection of items (components, units, etc.) whose

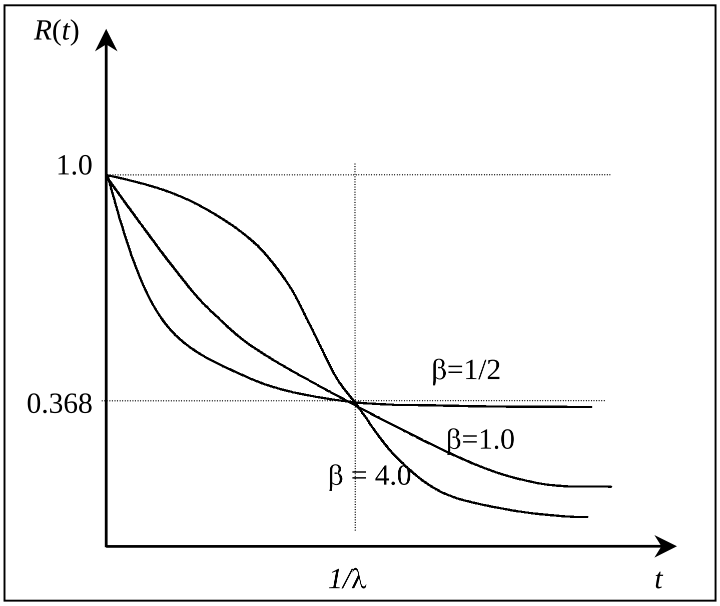

Figure 4. Reliability function for Weibull distribution

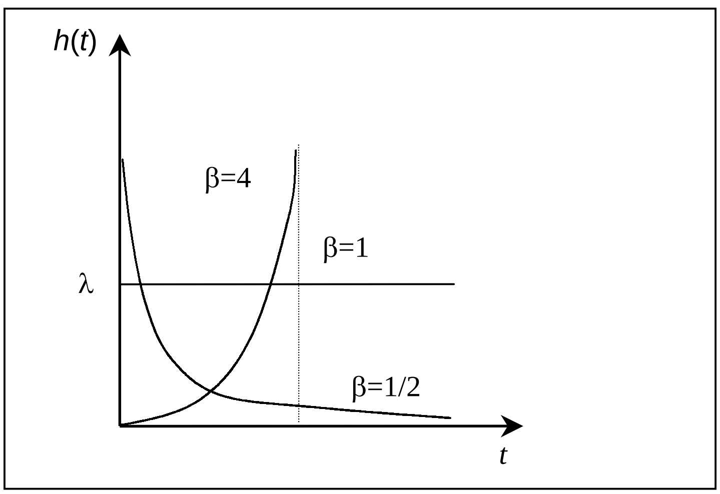

Figure 5. Hazard function for Weibull distribution

proper, coordinated function leads to its proper operation. In reliability analysis, it is therefore important to model the reliability of the individual items as well as the relationship between the various items to determine the reliability of the system as a whole. This ETL applies the reliability block diagram (RBD) method as outlined in MIL-STD-756B to model conventional probability relationships of collections of *independent* components and systems.

8. System Reduction

The number of discrete mechanical and electrical components in a lock and dam requires system reduction to reduce the vast complexity of numerous components into smaller groups of critical components. The reliability models should be developed to the level of detail for which information is available and for which failure rate (or equivalent) data can be applied. Functional elements not included in the mission reliability model shall be documented, and rationale for their exclusion shall be provided.

9. Component Reliability

The failure distribution appropriate to the specific electronic, electrical, electromechanical, and mechanical items should be used in computing the component reliability. In most cases, the failure distribution will not be known and the exponential or the Weibull may be assumed. The α and β parameters of the Weibull equation are normally empirically determined from controlled test data or field failure data. This ETL presents a procedure for estimating these values. If the β value in the Weibull function is unknown, a value of 1.0 should be assumed. The flat failure region of mechanical and electrical components is often much longer than the other two regions, allowing this assumption to be adequate. Once the component reliability values are determined, the RBD method is used to evaluate their relationship within the system to determine the total system reliability. Appendices D and E contain more information on determining component reliability. In Appendix F, the mechanical and electrical subsystem reliability data from Appendixes D and E are applied to the overall system to determine an overall lock and dam system mechanical and electrical reliability value.

10. System Risk Analysis Using Block Diagrams

The necessity for determining the reliability of a system requires that the reliability be considered from two perspectives, basic reliability and mission reliability. Both are separate but companion products that are essential to quantify the reliability of a system adequately. The incorporation of redundancies and alternate modes of operation to improve mission reliability invariably decreases basic reliability. A decrease in basic reliability increases the demand for maintenance and support. Basic reliability is normally applied to evaluate competing design alternatives.

a. *Basic reliability - Series System Model.* A basic reliability prediction is a simplified model that is intended to measure overall system reliability. It is used to measure the maintenance and logistic support burden required by the system. A basic reliability model is an all-series model. Accordingly, all elements providing redundancy or parallel modes of operation are modeled in series. In a series system, the components are connected in such a manner that if any one of the components fails, the entire system fails. Care should be taken when developing this type of model since the final value of the basic reliability of the system is inversely proportional to the number of components included in the evaluation; i.e., the more components there are, the lower the reliability. Such a system can be schematically represented by an RBD as shown in Figure 6.

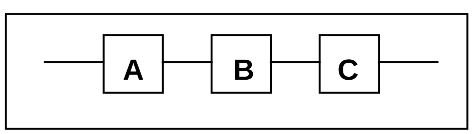

Figure 6. Series system

For a system with N mutually *independent* components, the system reliability for time t is

$$R_S(t) = R_A(t)*R_B(t)*R_C(t)*\ldots* R_N(t) \tag{10}$$

It can also be shown that if $h_s(t)$ represents the hazard rate of the system, then

$$h_s(t) = \sum_{i=1}^{n} h_i(t) \tag{11}$$

The failure rate of a series system is equal to the sum of the failure rates of its components. This is true regardless of the failure distributions of the components.

b. *Mission reliability*. The mission reliability model uses the actual system configuration to measure the system capability to successfully accomplish mission objectives. The mission reliability model may be series, parallel, standby redundant, or complex.

(1) *Parallel system model*. In a parallel system, the system fails only when all of the components fail. Such a system is represented in Figure 7. In this configuration, the system will still perform if at least one of the components is working.

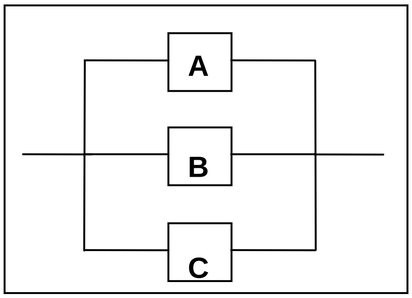

Figure 7. Parallel System

The reliability for the system is given by

$$R_S(t) = 1 - [1 - R_A(t)][1 - R_B(t)][1 - R_C(t)] \qquad (12)$$

or,

$$R_S(t) = 1 - \prod_{i=1}^{N} [1 - R_i(t)] \qquad (13)$$

A more general form of a parallel system is the "*r* out of *n*" system. In this type of system, if any combination of *r* units out of *n independent* units arranged in parallel work, it guarantees the success of the system. If all units are *identical*, which is often the case, the reliability of the system is a binomial summation represented by

$$R_S(t) = \sum_{j=r}^{n} \binom{n}{j} R(t)^j \, [1 - R(t)]^{n-j} \qquad (14)$$

where

$$\binom{n}{j} = \frac{n!}{j!(n-j)!} \qquad (15)$$

The hazard rate for parallel systems can be determined by using

$$h_s(t) = \frac{-\,\mathrm{d}\,ln\,R_s(t)}{dt} \tag{16}$$

or

$$h_s(t) = \frac{-\,\mathrm{d}\,ln\left\{1-\prod_{i=1}^{N}[1-R_i(t)]\right\}}{dt} \tag{17}$$

The result of $h_s(t)$ becomes rather complex and the reader is referred to the reference literature.

(2) *Standby redundant system.* A two-component standby redundant system is shown in Figure 8. This system contains equipment that is in primary use and also equipment standing idle ready to be used. Upon failure of the primary equipment, the equipment standing idle is immediately put into service and switchover is made by a manual or automatic switching device (SS).

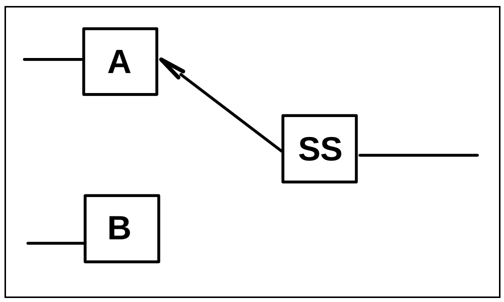

Figure 8. Standby redundant system

The system reliability function for the exponential distribution can be calculated for a two-component, standby redundant system using the following equation:

$$R_S(t) = R_A(t) + \frac{[\lambda_A R_B(t)]}{\left(\lambda_A+\lambda_{SS}+\lambda_B'-\lambda_B\right)}\left\{1-exp[-\left(\lambda_A+\lambda_{SS}+\lambda_B'-\lambda_B\right)d_i t]\right\} \tag{18}$$

where

λ_A = hazard rate of A

λ_{SS} = hazard rate of switching device

λ_B' = hazard rate of the standby equipment while not in use

λ_B = hazard rate of B

d_i = duty factor for respective failure rate

(3) *Complex system models.* Complex systems can be represented as a series-parallel combination or a non-series-parallel configuration. A series-parallel RBD is shown in Figure 9. This type of system is analyzed by breaking it down into its basic parallel and series modules and then determining the reliability function for each module separately. The process can be continued until a reliability function for the entire system is determined. The reliability function of Figure 9 would be evaluated as follows:

$$R_1(t) = (1 - \{[1 - R_{A1}(t)]\ [1 - R_{B1}(t)]\ [1 - R_{C1}(t)]\}) \ast R_{D1}(t) \tag{19}$$

$$R_2(t) = (1 - \{[1 - R_{A2}(t)]\ [1 - R_{B2}(t)]\}) \ast R_{D2}(t) \tag{20}$$

$$R_S(t) = (1 - \{[1 - R_1(t)]\ [1 - R_2(t)]\}) \tag{21}$$

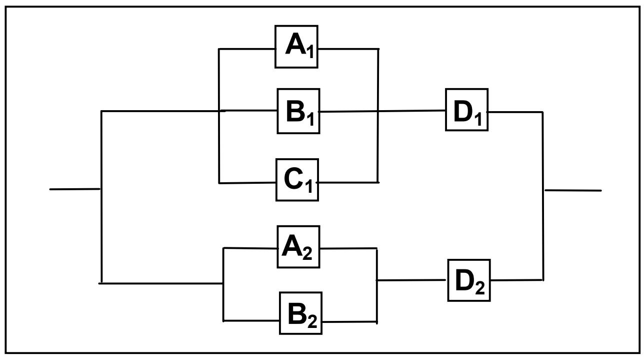

Figure 9. Series-parallel system

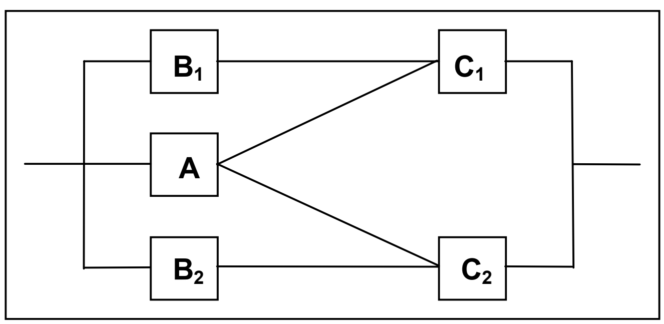

Figure 10. Non-series-parallel system

A non-series-parallel system is shown in Figure 10. One method of analyzing non-series-parallel systems uses the following general theorem:

$$R_S(t) = R_S(\text{if } X \text{ is working})\ R_X(t) + R_S(\text{if } X \text{ fails})\ [1- R_X(t)] \tag{22}$$

The method lies in selecting a critical component (X) and finding the conditional reliability of the system with and without the component working. The theorem on total probability is then used to obtain the systems reliability (see Appendix G).

11. Recommendations

It is recommended that the procedures contained herein be used as guidance for assessing reliability of navigation lock and dam mechanical and electrical equipment. It shall be used to quantify reliability and risk for decision analysis so that upgrade or rehabilitation alternatives can be evaluated.

12. Additional Information

Much of the work covered by this ETL is still under development. The Lock and Dam Equipment Survey Web site and other reliability-related Web sites are listed in Appendix B. The latest information pertaining to the work described herein can be obtained from CECW-EI.

FOR THE DIRECTOR OF CIVIL WORKS:

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7 Appendices
APP A - References
APP B - Reliability-Related Internet Web Sites
APP C - Merged Failure Data
APP D - Mechanical Equipment Example
APP E - Electrical Reliability Example
APP F - Example of Lock and Dam Mission Reliability
APP G - Non-Series-Parallel System Analysis